LUNAR GRAVITY: APOLLO 16

W. L. SJOGREN and R. N. WIMBERLY
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., U.S.A.

and

W. R. WOLLENHAUPT
Johnson Space Center, National Aeronautics and Space Administration, Houston, Tex., U.S.A.

(Received 22 April, 1974)

Abstract. Reduction of doppler radio tracking of the orbiting spacecraft has shown consistency with Apollo 14 data results and has revealed new gravity anomalies. Large craters are negative anomalies while wrinkle ridge regions are positive. The Central highlands are mostly a positive anomaly except for the Apollo 16 landing site, which is in a negative area. A gravity high northwest of Theophilus is not easily explained.

New gravity results over a 50-km band from 70° E long. to 70° W long. have been deduced from doppler radio tracking of the orbiting Apollo 16 Command and Service Module (CSM). This report is the third in a series of similar gravity reductions (i.e., Apollo 14 (Sjogren *et al.*, 1972c) and Apollo 15 (Muller *et al.*, 1974), which will be followed by a fourth on Apollo 17. All four gravity zones (Apollos 14, 15, 16, 17) are nonredundant except for five small areas where the trajectories for each mission cross over the others. These areas provide points for cross-checking the consistency of the data and show excellent agreement in all cases. The reduction techniques are precisely those described in (Sjogren *et al.*, 1971) or (Sjogren *et al.*, 1972a) and will not be elaborated on here, other than to say that the high-frequency velocity variations (i.e., <0.1 m s^{-1} over 30–300 s) for each orbit are differentiated for accelerations or gravity profiles and then contoured.

The doppler data for the following results are from the low-altitude orbits 3 through 15, where the CSM had a 20-km altitude at periapsis. The typical altitude history for one orbit is shown in Figure 1. Since resolution is almost directly proportional to spacecraft altitude, the eastern portion of the gravity zone will be better defined as well as having larger gravity amplitudes. There were three orbits (8, 12, and 13) that were not used due to data corruption by the attitude control system or spacecraft maneuvering. This left approximately 3000 good doppler points spaced about 15 km apart and much closer where the orbits overlap near the Apollo 16 landing site (i.e., narrow portion of gravity zone).

The results are presented in Figure 2 as contoured line-of-sight accelerations* at spacecraft altitude. No corrections have been applied to account for geometry, altitude or the least-squares filtering effects (Gottlieb, 1970), which reduce the larger amplitudes

* Line-of-sight acceleration is the component of the acceleration vector projected on the spacecraft-Earth observing station line (100 mgal$=$1 mm s^2).

The Moon **11** (1974) 35–40. *All Rights Reserved*

(both positive and negative) by 20–30%. Geometric distortion is negligible near the central meridian, but becomes appreciable in the 50°–70° long. region (i.e., 1°–2°).

The following comments are made concerning the results shown in Figure 2:

(1) Oceanus Procellarum does not exhibit any large or particularly prominent anomaly. The Flamsteed region near −50° long. has a negative anomaly of −30 mgal.

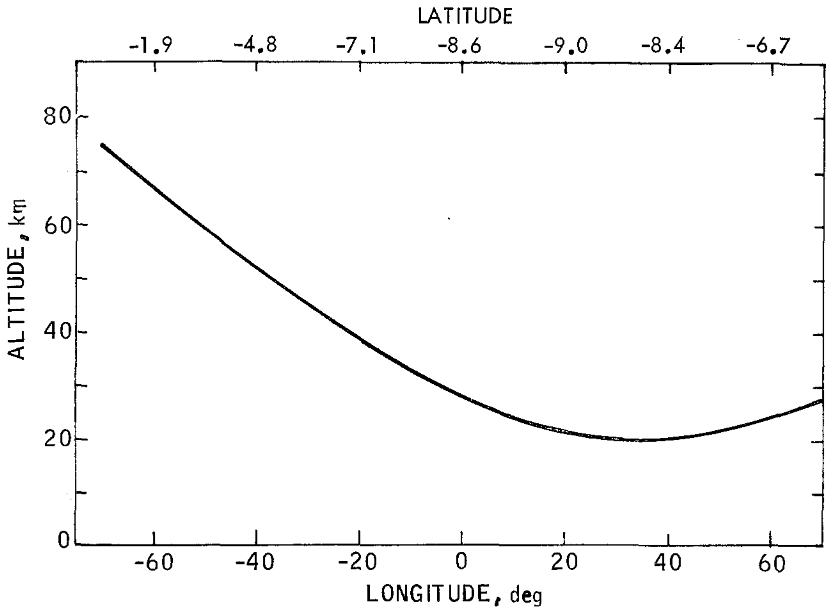

Fig. 1. Apollo 16 spacecraft altitude profile, revolutions 3–15.

(2) There is a positive high of 73 mgal at −33° long. with a relatively steep gradient over Montes Riphaeus. The peak may be associated with the wrinkle ridge structure between −34° and −33° long.

(3) At −16° long. the Fra Mauro area is centered in a −52-mgal low. A local high of −35 mgal is just east of this at −12.5° long. and possibly associated with the ridge structure in the area.

(4) Mare Nubium is revealed again as a negative anomaly with −61 mgal. (Sjogren *et al.*, 1972b).

(5) A local gravity high occurs on the western flank of the crater Ptolemaeus, while a −98-mgal measure is obtained for the central region. This is very consistent with previous results from Apollos 12 and 14 (Gottlieb *et al.*, 1970; Sjogren *et al.*, 1972c.

(6) The Apollo 14 and 16 mission surface tracks were very nearly overlappping from 5° long. to 25° long. The Apollo 14 altitude was 10 km lower at 5° long. and about the same at 25° long., so its resolution is slightly better and the acceleration amplitudes are higher at the smaller longitudes (Sjogren *et al.*, 1972c). The highs and

lows occur with remarkably good agreement as shown in Table I. The highland region is generally a positive anomaly except for the small negative region at 16° long. The 107-mgal anomaly at 24.5° long. does not correlate well with any visible feature.

(7) The maria between Mare Tranquillitatis and Mare Nectaris are mostly in a positive anomaly area.

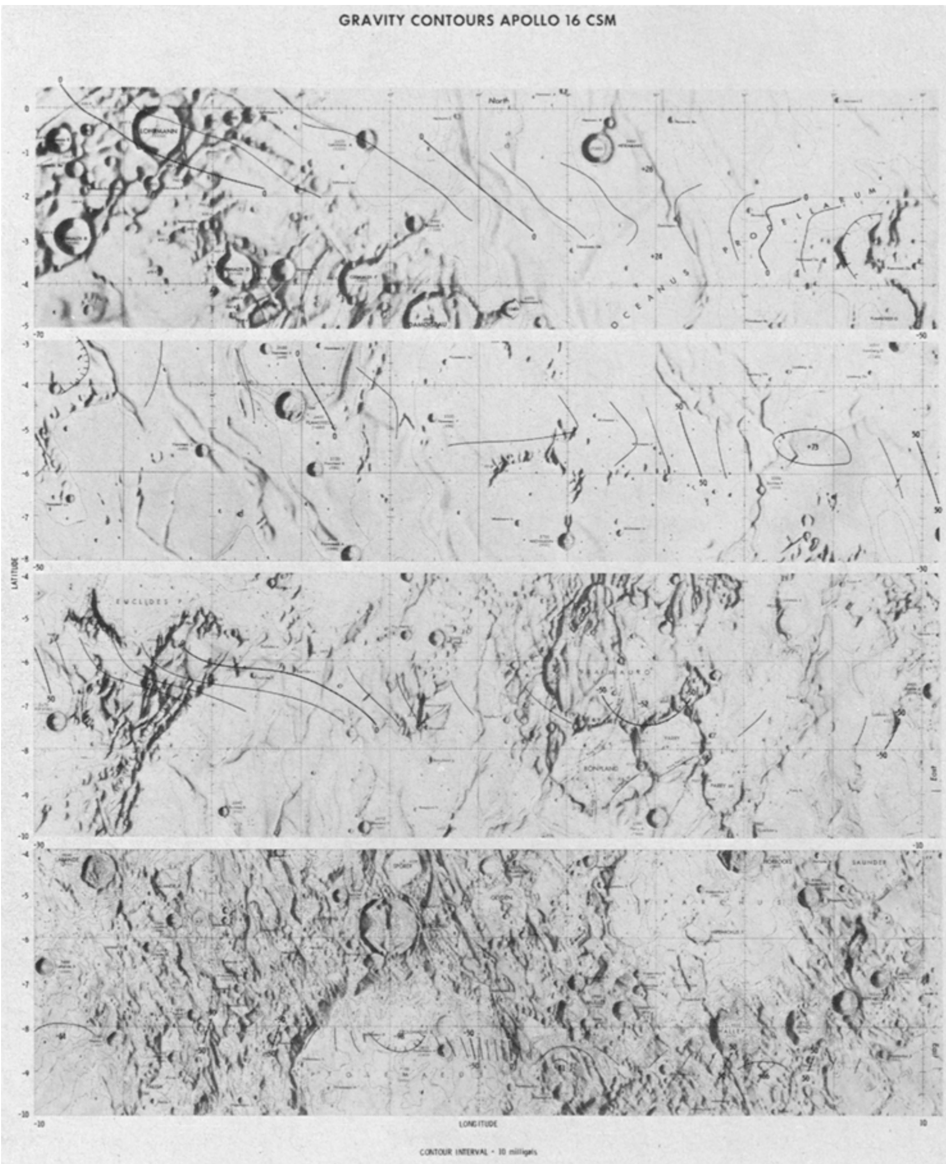

Fig. 2a.

TABLE I

Comparison of accelerations obtained on Apollos 14 and 16

Longitude (deg)	Acceleration (mgal)	
	Apollo 14	Apollo 16
7	90	66
12	50	40
16	−40	−34
20	60	66
24	80	107

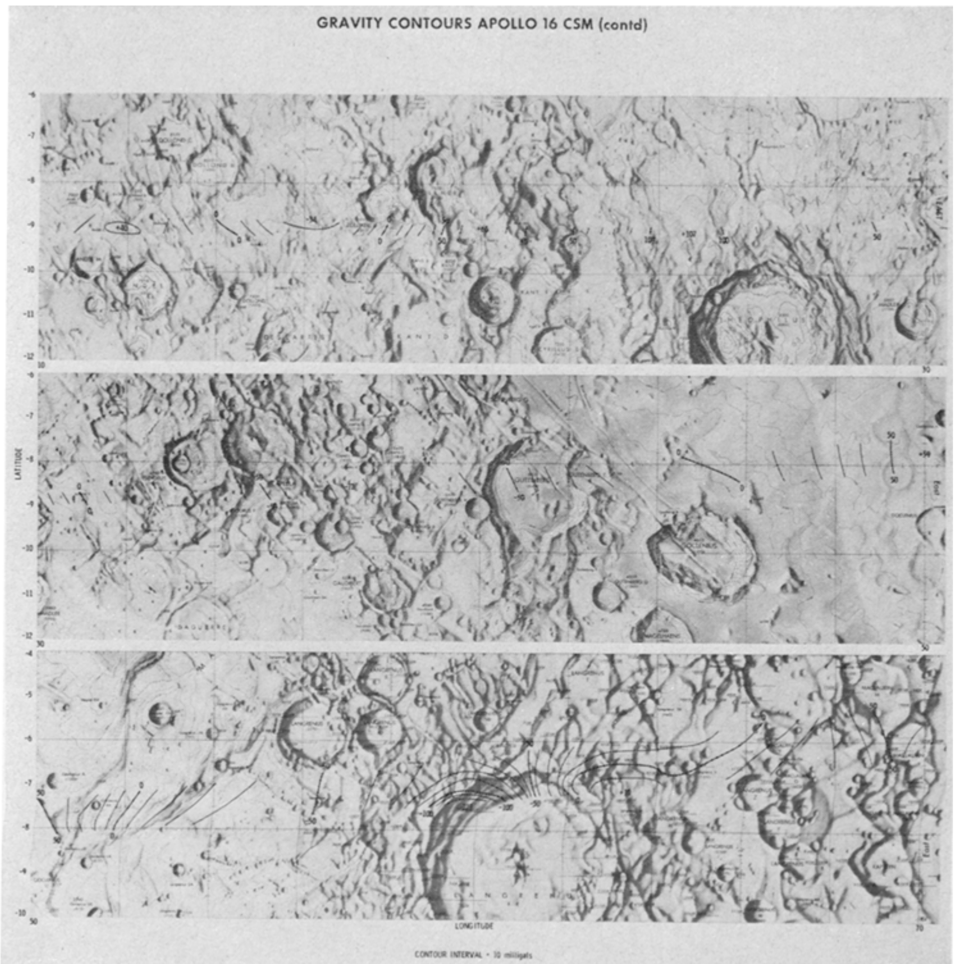

Fig. 2b.

Figs. 2a–b. Apollo 16 gravity contours from line-of-sight acceleration profiles of revolutions 3–15.

(8) The highland terrain from 32° to 42° long. has a −72-mgal anomaly centered at 37° long. This negative anomaly could possibly be associated with a Nectaris negative ring structure; however, the ring is interrupted as noted by the previous item (7).

(9) Mare Fecunditatis has a positive anomaly of 59 mgal that appears to correlate with the ridge structure at 51° long. (Geometry starts to move the peak anomaly a degree or so toward the prime meridian at these longitudes.)

(10) The distortion due to geometry is clearly evident for the crater Langrenus, which has a −127-mgal anomaly displaced about $1\frac{1}{2}$°.

The Apollo 16 gravity mapping has certainly shown the complexity of gravity variations over the original mapping in Muller and Sjogren (1968), where the ringed maria were large positive anomalies and the irregular maria were essentially zero or negative anomalies. There are now gravity highs of 60–70 mgal detected at wrinkle ridge formations in Oceanus Procellarum (34°W long.) and Mare Fecunditatis (51°E long.), indicating mass excesses due presumably to volcanic extrusions (Marshall, 1963; Elston, 1972). Also the unusual high of 107 mgal in a low maria region (altimetry (Sjogren and Wollenhampt, 1973) northwest of Theophilus does not correlate with any visible feature, suggesting a dense buried structure. The Descartes landing site of Apollo 16 was selected for sampling the highlands; however, gravity observations yielded a negative anomaly and, therefore, show it in direct contrast with most of the highlands that are positive at least in these data and those in Sjogren *et al.* (1972b).

Apollo 16 has definitely verified the Apollo 14 results and revealed that the large crater Langrenus is a strong negative anomaly consistent with twenty other large craters sampled to date. The near-center profile over the crater Ptolemaeus, which then crosses Mare Nubium, is a striking example of differences between gravity and topography, which is opposite to the mascon situation. (i.e., a mascon is a large positive anomaly in a topographic low, and Ptolemaeus is a large negative anomaly in a topographic high.) The floor of Ptolemaeus is 1 km above Mare Nubium (Sjogren and Wollenampt, 1973) (laser altimeter results from Apollo 16 orbits 17, 28, 37, 46, and 59, which are opposite to the erroneous ACIC LAC77 elevations*); yet the anomaly in Ptolemaeus is more negative and not at all correlated with the topography. An explanation might be that Ptolemaeus was filled by a lower density material as suggested by Zisk (1972). There may be some evidence for this from the following modeling study, but other facts imply that it is far from conclusive.

Disk mass deficiencies for both Langrenus and Ptolemaeus were estimated in a dynamical reduction using the raw data. Calculations for the density** of the crater material necessary to fill the craters to a level corresponding to adjacent surface topography resulted in 3.05 g cm^{-3} for Langrenus and 4.0 g cm^{-3} for Ptolemaeus. The parameters for Langrenus were quite well defined (R. B. Baldwin, 1963), but those for Ptolemaeus were difficult to assess. Had the material defect depth been chosen as

* Lunar Chart LAC 77, Aeronautical Chart and Information Center, St. Louis, Missouri.

** Volumes were calculated on frustum with the following values. Langrenus: Bottom = 45 km radius; top = 62 km; total depth = 4.05 km − 0.68 km = 3.37 km; mass = -0.96×10^{20} g. Ptolemaeus: Bottom = 65 km radius; top = 70 km; total depth = 1 km; mass = -0.56×10^{20} g.

1.3 km* for Ptolemaeus, the resulting density would be 3.1 g cm^{-3} (a realistic lunar density). However, the added material brings the anomaly only to zero, and additional material is required to produce a positive anomaly for the topographic relief of the highland area. This requirement seems to indicate that the present internal filling of Ptolemaeus may be less dense than its surroundings. On the other hand the Descartes Apollo landing site, which is topographically higher than the floor of Ptolemaeus (Sjogren and Wollenhampt, 1973), has a negative gravity anomaly. Possibly prior to the crater formation, the Ptolemaeus region itself may have been part of a negative highland anomaly associated with Mare Nubium. If such is the case, there is no need to argue for less dense material filling in Ptolemaeus. Langrenus, which is a relatively fresh and unfilled crater, has parameters that are all very consistent with known lunar facts.

References

Baldwin, R.B.: 1963, *The Measure of the Moon*, University of Chicago Press.
Elston, D.P.: 1972, Department of Interior United States Geological Survey, Geological Map of the Colombo Quadrangle of the Moon, 1-714 (LAC-79), Scale 1:1000000.
Gottlieb, P.: 1970, *Radio Science* **5**, 301.
Gottlieb, P., Muller, P. M., Sjogren, W. L., and Wollenhaupt, W. R.: 1970, *Science* **168**, 477.
Marshall, C. H.: 1963, Department of Interior United States Geological Survey, Geological Map and Sections of the Letronne Region of the Moon, 1-385 (LAC-75), Scale 1:1000000.
Muller, P. M. and Sjogren, W. L.: 1968, *Science* **161**, 680.
Muller, P. M., Sjogren, W. L., and Wollenhaupt, W.: 1974, *The Moon* **10**, 195.
Sjogren, W. L. and Wollenhaupt, W. R.: 1973, *Science* **179**, 275.
Sjogren, W. L., Gottlieb, P., Muller, P. M., and Wollenhaupt, W.: 1971, NASA SP-272 (National Aeronautics and Space Administration, Washington), p. 253.
Sjogren, W. L., Muller, P. M., and Wollenhaupt, W. R.: 1972a, *The Moon* **4**, 411.
Sjogren, W. L., Muller, P., and Wollenhaupt, W. R.: 1972b, NASA SP 315 (National Aeronautics and Space Administration, Washington), p. 24-1.
Sjogren, W. L., Gottlieb, P., Muller, P. M., and Wollenhaupt, W.: 1972c, *Science* **175**, 165.
Zisk, S. K.: 1972, *Science* **178**, 977.

* Volumes were calculated on frustum with the following values. Langrenus: Bottom = 45 km radius; top = 62 km; total depth = 4.05 km − 0.68 km = 3.37 km; mass = − 0.96 × 10^{20} g. Ptolemaeus: Bottom = 65 km radius; top = 70 km; total depth = 1 km; mass = −0.56 × 10^{20} g.